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(71) Applicant *(for all designated States except US)*: THE UNIVERSITY COURT OF THE UNIVERSITY OF EDINBURGH [GB/GB]; Old College, South Bridge, Edinburgh, EH8 9YL (GB).

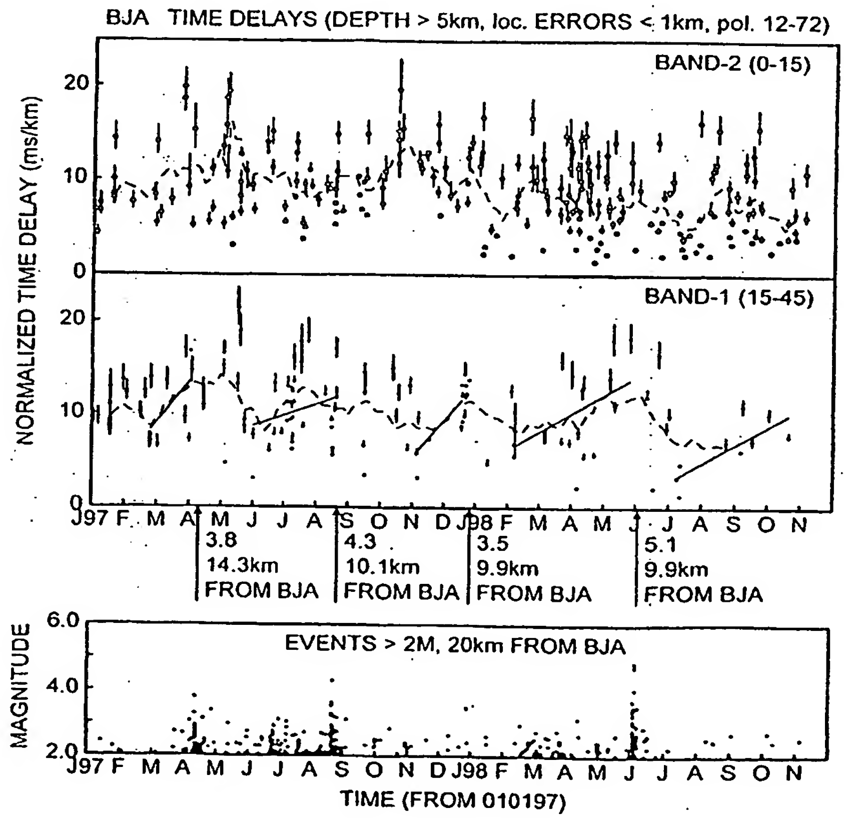
(72) Inventor; and
(75) Inventor/Applicant *(for US only)*: CRAMPIN, Stuart [GB/GB]; 4/7 Advocate's Close, Edinburgh EH1 1PS (GB).

(74) Agent: HANSON, William, Bennett; J.Y. & G.W. Johnson, Kingsbourne House, 229–231 High Holborn, London, WC1V 7DP (GB).

(54) Title: STRESS–FORECASTING OF SEISMIC EVENTS

(57) Abstract

A method for stress–forecasting of seismic events including earthquakes and volcanic eruptions comprises detecting, at at least one location at a first depth below the Earth's surface, shear–waves emitted from a seismic source at at least one angle, preferably less than about 50 degrees to the vertical, spaced horizontally from the at least one location and at a second depth greater than or equal to the first depth. Preferably, the shear–waves are detected at two locations in separate boreholes, and time–delays between orthogonal polarisations of the shear–waves are analysed.



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STRESS-FORECASTING OF SEISMIC EVENTS

BACKGROUND TO THE INVENTION

Given that earthquake prediction, in terms of the reliable estimation of the time, place and magnitude of a future large earthquake can on current understanding be largely excluded, alternative strategies for the mitigation of hazard to life and property are highly desirable.

Although the physical nature of critical behaviour had until recently not been identified, statistical evidence suggested that the Earth is close to a critical state, sometimes referred to as *self-organised criticality,* which would specifically exclude deterministic earthquake prediction. This has not prevented various schemes being advanced to implement earthquake prediction through detection of earthquake precursors, including sensitive vibration monitors, measurements of evaporation of groundwater through electric field gradients, plasma density fluctuations in the ionosphere and the monitoring of geomagnetic disturbances, amongst many others..

Such methods are not based on geophysics, are purely empirical, and very inaccurate. Prior to this disclosure, even post-analysis of measured data could not be reliably correlated to the incidence of earthquakes.

This invention is primarily directed to the forecasting of individual large earthquakes, in which phrase "individual" excludes foreshock series which may sometimes indicate that a large earthquake is imminent. Similarly "large" excludes isolated swarms of earthquakes where larger earthquakes in the sequence may sometimes repeat at frequent intervals with very similar locations and magnitudes. "Earthquake precursor" refers to observations of any physical phenomena that may indicate that a large earthquake is imminent. These phenomena are usually geophysical, although a wide range of other phenomena has sometimes been claimed to be precursors. Although in some circumstances such estimates may be useful they do not, and cannot, give time,

place and magnitude of future earthquakes. Precursors are irregular and unpredictable and schemes for routine warnings of earthquakes cannot be wholly based on observations of precursors.

Despite this demonstrable unpredictability, there is one precursory phenomenon that can be reliably monitored. No earthquake can occur without sufficient deformation energy accumulating in the crust to provide the energy released by the earthquake. Since the crust of the earth is relatively weak under shear, the stress released by a large earthquake necessarily accumulates over a very large volume of rock, for some indeterminate length of time, before the earthquake. Previous methods have sought to monitor this build up of stress, by making static measurements on both sides of known fault lines.

However, the absence of a suitable model for the underlying physical processes by which stress builds up, and how stress relates to criticality, has hampered such methods. Mechanical measurements of stress in general provide only localised single point measurements, and so require a large plurality of sensors to provide sufficient geographical coverage. Moreover, such measurements by their localised nature would be most valuable when made relatively close to a fault zone where the rock structure will tend to very complex and subsequent data analysis is therefore difficult and unrepresentative.

The current invention provides for a new strategy of forecasting earthquakes based on firm understanding of the underlying micro and macro geophysical phenomena leading to criticality.

The inherent unpredictability of large earthquakes appears to close one avenue in our quest for warnings of earthquakes. However, observations and analysis of shear-wave splitting suggest that it is possible to forecast the proximity in space and time of large earthquakes by monitoring the accumulation of stress necessary before earthquakes can occur. A new understanding of non-catastrophic deformation of in situ rock shows that changes in stress at depth in the crust can be monitored directly by changes in shear-

wave splitting. See Crampin, S.: "Stress-forecasting: a viable alternative to earthquake prediction in a dynamic Earth", *Transactions of the Royal Society of Edinburgh: Earth Sciences*, 89, 121-123, 1998. These techniques would allow the build-up of stress to be identified in relatively intact homogeneous rock well away from the complications of the immediate source zone so that the potential for a large earthquake can be forecast. There is now a substantial body of theory, observation and practice that supports this "forecasting" concept.

Geophysical research has shown that micro-cracks in in-situ rocks dilate as stress builds up before earthquakes until a level of fracture criticality is reached when the rocks fracture and the earthquake occurs. As rocks are weak to shear stress, crack alignments and proximity to criticality are pervasive over very large volumes of the crust around the eventual source zone. The changes in micro-crack dilation can be recognised by monitoring seismic shear-wave splitting along appropriate ray paths. Initially, it was assumed that increasing stress would increase the aspect ratios of micro-crack distributions (make cracks swell or dilate) which could be monitored by specific changes in the three-dimensional pattern of shear-wave splitting. Recently, a tightly-constrained theoretical anisotropic poro-elasticity (APE) model for prefracturing deformation has been developed, where the driving mechanism is fluid migration along pressure gradients between neighbouring grain-boundary cracks and low aspect-ratio pores at different orientations to the stress field.

APE matches or is compatible with a large range of seismic and crack phenomena. including the effects on shear-wave splitting of the build-up of stress before earthquakes. If the increase can be monitored and the level of fracture criticality estimated, the time of the earthquake can be forecast; and the magnitude of the earthquake can be estimated from the slope of the increase of stress and the duration of the build up. We call this process of estimating the time and magnitude of future large (or larger) earthquakes, *stress-forecasting*. The location cannot be estimated directly, but once it is known that a large earthquake is imminent, local studies can often estimate the epicentre. The particular phenomena has been recognised with hindsight (using shear-waves from natural earthquakes recorded by seismic stations on the

surface.) before three earthquakes in USA, one in China, and now routinely before (five) earthquakes in SW Iceland (as of 23rd March 1999). Well-correlated retrospective fits have been obtained between orthogonal wave time lags and stress build-up. Further, successful forecasting has now been demonstrated. Because of scatter in the data, an earlier, smaller magnitude, to later, larger magnitude window is defined. The range of azimuths and incidence angles is critical for monitoring stress-induced changes to micro-crack geometry.

Stress-aligned shear-wave splitting (seismic birefringence) is observed with very similar characteristics in almost all igneous, metamorphic, and sedimentary rock, below from about 500 m to 1 km depth in the Earth's crust. The polarisations of the faster split shear-waves are approximately parallel to the direction of maximum compressional stress. Geometrical constraints indicate that the splitting is controlled by the densities and aspect-ratios of distributions of the stress-aligned fluid-saturated grain-boundary cracks and low aspect-ratio pores present in almost all rocks. Consequently, shear-wave splitting can be used to monitor the effects of the stress build-up before earthquakes and *stress-forecast* future large earthquakes

Since 1980, stress-aligned shear-wave splitting has been widely observed in crystal rocks as a result of the fluid-filled grain boundary cracks and low aspect ratio pores in virtually all rocks becoming effectively aligned by the stress-field. There are only a few well-understood exceptions where rocks do not display stress-aligned shear-wave splitting. These distributions of aligned "voids" are known as *extensive-dilatancy anisotropy* or *EDA* and the individual voids as *EDA -cracks.*

The behaviour and characteristics of shear-wave splitting appear to be independent of the porosity. This is because shear-wave splitting is controlled by the crack and low aspect-ratio pore distributions, whereas porosity is controlled principally by the volume of the pores (this is supported by theoretical APE studies). Shear-waves are extremely sensitive to modifications to the micro-scale geometry of fluid-filled EDA cracks and variations in shear-wave splitting have been observed before earthquakes and other phenomena.

When pervasive distributions of stress-aligned fluid-saturated micro-cracks in *in-situ* rocks were first suggested, it was recognised that EDA-cracks would be compliant and respond to changes in stress before earthquakes. Since shear-wave splitting is sensitive to crack geometry, temporal changes in shear-wave splitting were sought. The table indicates the approximate expected response of micro-cracks to changes of stress and the corresponding changes in the behaviour of shear-wave splitting.

Changes in Stress	Corresponding changes in crack geometry	Corresponding changes in shear-wave splitting
1) Change of direction of principal axes of stress	Change in orientation of dilated (open) microcracks	Change in direction of shear-wave polarisations
2) Major (abrupt) increase in compressional stress	Anelastic increase in number of cracks, implying increase in crack density	Increase in time-delays over whole of shear-wave window but specifically along ray path directions within ±15° of the average crack face
3) Marginal (gradual) increase in compressional stress	Elastic increase in crack aspect-ratios	Increase in time-delays along ray path directions between 15° and 35°-45° to the average crack face
4) Marginal increase in pore-fluid pressures	Elastic increase in crack aspect-ratios	Increase in time-delays along ray path directions between 15° and 35°-45° to the average crack face

Apart from changes in shear-wave polarisations indicating changes in stress directions, the key feature is the variation of the pattern of time-delays between split shear-waves in the shear-wave window at the free surface between ray-path directions less than and more than 15° to the face of the nearly-vertical cracks. The shear-wave window is a cone of directions defmed by ray paths with angles of incidence at the free surface of less than 35° to 45°; the exact angle depending on the ray-path curvature through near-surface weathering and stress-decompression anomalies, and the Poisson's ratio of the un-cracked matrix rock. Shear-waves incident within this window at the surface are not distorted by *S-to-P* conversions and have the same waveforms as the incident waves.

The behaviour of shear waves propagating through a distribution of vertical cracks with

a range of strike directions is very similar to the behaviour through wholly parallel vertical cracks oriented about the mean direction of crack strikes (the direction of minimum horizontal stress), so the effects of cracks in the crust can be approximated by the behaviour of parallel cracks. Increases of crack density show an overall increase in time-delays over the whole of the shear-wave window. Changes in aspect ratio are concentrated in directions between about 15° and 45° to the average crack plane, whereas directions less than 15° to the crack plane remain almost constant. It was this different behaviour at more than, and less than, 15° to the crack plane before the earthquakes in Fig. 1 that show the effects expected for increasing and then decreasing crack aspect-ratios. Various examples of temporal changes in shear-wave behaviour indicate that the Earth is dynamic and responds to changing conditions by modifying micro-crack geometry. Because the micro-crack geometry is similar below from about 500 m to 1 km depth in almost all rocks, the evolution of micro-cracked rock can be calculated by a model which is partially independent of rock type, porosity, and initial crack density.

APE models the evolution of stressed fluid-saturated micro-cracked rocks under changes of stress and other parameters. The effects of increasing stress can be resolved into increasing crack density and/or increasing aspect ratio (crack swelling). APE modelling confirms that the immediate effect of increasing (horizontal) stress on rocks is to increase average aspect ratios in distributions of (approximately) parallel vertical micro-cracks. This increases the average time-delays in the double band, Band-1 (ray paths between 15° and 45° to the crack plane), of directions across the shear-wave window. Time-delays in the remainder of the shear-wave window (Band-2), the solid angle with ray path directions within ±15° to the crack plane, are controlled primarily by the crack density of the crack distribution. The data in Band-2 show no simple correlations with earthquakes.

The term "increasing aspect-ratios" is a simplified description strictly valid only for distributions of parallel cracks with hexagonal anisotropic symmetry (transverse isotropy). APE modelling suggests that crack distributions are specified by three-dimensional patterns of variations in aspect-ratio. Such distributions have orthorhombic

anisotropic symmetry and the effects of changing stress conditions are more complicated than simple changes in crack density or changes in aspect ratio. However, the behaviour of weak orthorhombic distributions of cracks and weak hexagonal distributions of (parallel) cracks is similar for ray paths within the shear-wave window, and this is the justification for interpreting the effects as changes in aspect-ratio and changes in crack density.

Also, from geometrical considerations it might be expected that the suggested crack changes for increasing stress would only be valid before strike-slip earthquakes for cracks perpendicular to the minimum horizontal compressional stress. However, approximately parallel shear-wave polarisations have been observed within the shear-wave window in an extremely wide range of tectonic and stress environments, including above predominately thrust earthquakes. No known observations exist which suggest nonparallel shear-wave polarisation's anywhere below 1 km. This suggests that the minimum differential stress (perpendicular to the crack face) is likely to be effectively horizontal in almost all circumstances. Fortunately, if all polarisations were significantly different because of different stress-field conditions, there would still be sufficient information in adequate observations of polarisations and time-delays for the appropriate correct interpretation to be made.

Observations suggest that the earth's crust is compliant and that the build-up of stress before an earthquake modifies micro-crack geometry that can be monitored by analysis of shear-wave splitting. As rock is weak under tensional stress and fractures rather easily, the amount of energy released by a large earthquake is built-up and stored over an enormous volume of rock. Probably many millions of cubic kilometres before an M = 8 earthquake and, in principle, the increase in stress should be recognisable by analysis of shear-wave splitting along appropriate ray paths almost anywhere within this large volume. In particular, the build-up of stress should be recognisable in comparatively homogeneous crustal blocks well away from the complications associated with faults, shear zones, and immediate epicentral preparation zones.

Repeated observations of shear-wave splitting over a specified range of optimum

directions are required. The monitored rock needs to be below the depth where the vertical stress equals the minimum horizontal stress to avoid near-surface stress-relief heterogeneities. In addition, the uppermost kilometre of the crust is typically characterised by heterogeneities, inter-granular micro-cracks, and fractures which cause severe seismic attenuation and scattering. This means that shear-wave signals either generated or recorded at the free surface are usually limited to frequencies less than, typically, 100 Hz, and such frequencies would require long source-receiver ray paths in order to obtain sufficient resolution to reliably monitor changes of less than one ms/km with all the complications of near-surface heterogeneities and the need for powerful source generators for long ray paths.

Conventional shear-wave reflection surveys, and various vertical-seismic-profiles (VSPs), walk-away VSPs, and reverse VSPs would not yield appropriate resolution. They would also require multiple surface sites which would not necessarily be available in those regions of high levels of industrial, residential, and cultural activity where earthquake "stress-forecasting" is most needed.

Note also that stress is intrinsically anisotropic. Unless this anisotropy is identified correctly, the anisotropy will impose directional variations in behaviour that may severely distort almost all other observations. Thus anisotropy tends to degrade observations interpreted assuming isotropy. One of the advantages of monitoring shear-wave splitting is that anisotropy is an essential part of the behaviour so that instead of degrading it enhances the data by providing additional interpretable information.

Failure of stressed micro-cracked rocks will not occur until fracture criticality is exceeded, either locally or regionally. Observations and APE theory suggest that fracture criticality is associated with the percolation threshold, which is the crack density at which there is a statistical likelihood of through-going crack. Although percentages of shear-wave anisotropy and inferred crack densities are directly associated in each rock and are largely independent of rock type or porosity, time-delays even when normalised to ms/km are particularly sensitive to the shear-wave velocities and Poisson's ratios of the un-cracked matrix rock and the uniformity or

otherwise of the crack distributions along the ray path. The "normal" range of time-delays associated with temporal changes appears to be from about 2 ms/km to between 4 and 8 ms/km (2 to 20 ms/km in Iceland) where the upper end of the range is expected to be just below the value of fracture criticality for the particular rock-mass. The range is probably dependent on local petrological, geological, and tectonic conditions. If the value could be identified for any particular area and if this value is stable, then proximity to criticality of any seismic episode would provide a valuable guide to the timing of a large earthquake.

Stress-forecasting uses changes in shear-wave splitting in Band-1 of the shear-wave window to monitor crack aspect-ratios and estimate the time and magnitude that crack distributions reach fracture criticality. There are three principal hypotheses.

1) The build-up of stress before earthquakes causes progressive changes in aspect ratios until a level of cracking, known as fracture criticality, is reached and the earthquake occurs.

2) Rock is weak to tensile stress, so the effects of the stress build up before earthquakes are pervasive over large volumes of the crust, and the approach to fracture criticality can be monitored by analysing shear-wave splitting at substantial distances from impending epicentres.

3) For a steady stress/strain input, from a moving plate, say, the magnitude of the impending earthquake is a function of the rapidity and duration of the stress build-up before fracture criticality is reached: if stress accumulates in a small volume, the build-up is fast but the resulting earthquake is comparatively small; whereas if stress accumulates over a larger volume, the increase is slower but the eventual earthquake is larger.

SUMMARY OF THE INVENTION

It is an aim of the invention to stress forecast seismic events, such as large earthquakes

and volcanic eruptions, using controlled source seismology (preferably artificial sources) in stress-monitoring sites, with particular geometries of source to receiver(s).

The present invention provides a method for stress forecasting a seismic event comprising detecting, at at least one location at a first depth below the Earth's surface, shear-waves emitted from a seismic source at at least one angle between 0° and 90° to the vertical, the source being spaced horizontally from the at least one location and at a second depth greater than or equal to the first depth.

If the source and detection locations are in boreholes then the shear-wave splitting is monitored in a particular geometry between boreholes, rather than at the localised site of individual boreholes.

By monitoring changes in fluid-saturated micro-cracks the approach of the critical state when the rocks will fracture is identified. The micro-crack changes are identified through shear-wave splitting and the technique is applicable irrespective of the absolute magnitudes of rock stress.

Monitoring shear-waves below the surface overcomes the difficulties in using surface recorders or sources due to attenuation and scattering, affecting in particular short-period signals. Preferably, said first and second depths are both greater than about 500 m and more preferably they are greater than 1 km. Said second depth is preferably greater than about 1.5 km. Advantageously, shear-waves propagating at less than 50°, preferably between 15° and 45°, to the vertical are detected.

Preferably, time-delays between orthogonal polarisations of the shear-waves are analysed, to deduce information concerning the stress condition of surrounding rock, the approach to criticality and the likelihood of a major seismic event. Preferably two features of variations in shear-wave time-delays are used to provide the possible occurrence time and magnitude of impending earthquakes: the duration of the increase in time-delays; and the size of the time-delay relative to fracture criticality.

The invention also provides apparatus for stress-forecasting a seismic event, comprising at least one borehole seismic source and at least one borehole seismic receiver, the at least one source being deeper than or at the same depth as the at least one receiver and the at least one source being adapted to generate shear waves upwardly at 0° to 90° to the vertical in the direction of the at least one receiver

Preferably, the azimuthal direction of the at least one receiver from the at least one source is at an angle greater than 30°to an average crack strike, and more preferably greater than 45° or 60° to the average crack strike.

In a preferred embodiment a monitored site comprises one said seismic source and two said seismic receivers. In a preferred embodiment, the two receivers are placed in separate wells at azimuths spaced in angle from the source well, preferably at azimuths within 90°, say approximately 60°, apart.

A plurality of monitored sites may be used to provide increased geographical coverage of an active region.

Thus, for optimal splitting the receiver wells should be in azimuths approximately ±30° from the direction of minimum compressional stress of the surrounding rock, but it should be understood that all other azimuths within ±90° are within the scope of the invention.

The controlled seismic source is preferably deployed in a vertical borehole, at a depth in excess of 1 km, preferably of the order of 2 km. This is preferably a temporary deployment only for the duration of the measurement to allow the use of equipment that does not have to be rated for continual exposure to high temperature environments. The receivers are advantageously placed in separate boreholes at depth and distance combinations that yield the appropriate range of angles (i.e. between 0 and 50 degrees) from the vertical axis for the seismic ray-paths, preferably but not restricted to SV waves. However these installations should be chosen according to local geology to place the receiver in an area of relatively intact and homogeneous rock. This is likely

to be true only at depths in excess of 0.5 km, preferably at approximately 1 km. These receiver installations are preferably permanent, to yield repeatability of seismic receiver performance.

The sensitivity of shear-wave velocities to the crack distributions along the ray path are used as an analogue measurement of the stress state of rocks lying between the source and receivers. Any deviation from the "normal" range of time-delays associated with temporal changes indicates an approach to the value of fracture criticality for that particular rock-mass. The range of values will be dependent on local petrological, geological, and tectonic conditions. Proximity to criticality provides a valuable guide to the timing of a large earthquake.

Stress-forecasting is based on a new understanding of the essentially anisotropic nature of rock deformation based on micro-scale physics, where the anisotropy is exploited in analysis of shear-wave polarisation's and time-delays. Since it is a physics-based system, it allows reliable and correct interpretation of anomalous or irregular behaviour. This invention provides a method to practically implement stress-forecasting.

BRIEF DESCRIPTION OF THE DRAWING

The invention will now be described in more detail, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 comprises graphs of shear-wave time delays and seismic events at a first station; and

Figure 2 comprises graphs of shear-wave time delays and seismic events at a second station.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

It is envisaged that existing wells in suitable locations and of sufficient depth would be used for the seismic wave transmitter. If no adjacent wells were available for the receivers, these could be sunk in locations at suitable azimuths to the main borehole.

Any seismic source which could yield a broad spectrum of seismic shear waves could be considered,. These include but are not limited to a simple conventional 'air-gun' source, which creates an explosive air bubble or an orbital vibrator, for example as manufactured by Conoco, which has a spinning eccentric disc rotated successively clockwise and anti-clockwise.

Any device normally used for seismic measurements could be considered as a receiver, including but not restricted to three-component seismic recorders of velocity, acceleration, or displacement which can be processed to yield two orthogonal shear-wave signals. Further processing of the received signals is also required to yield a figure for the phase difference, or difference in transit time between the two orthogonal seismic wave components. The receiver could be suitably clamped, cemented or sanded in place.

The use for the method is to provide the removal of the unexpected nature of earthquake hazard. Repeat surveys would indicate whether a large earthquake were expected for, perhaps (depending on area) M=5 earthquake within ~30 km, M=6 within 80 km, M=7 within 150 km, and M=8 within 300 km, where all these distances could vary by at least 100%.

If stress were increasing, stress-monitoring sites will indicate the approximate time and magnitude of the future earthquake. It could not indicate location, but local investigations could well do so. This would allow measures to be taken; to minimise hazard, develop evacuation procedures, shore up vulnerable buildings, and shutdown procedures for services.

Forecasts could be issued in a crescendo of urgency: a possible earthquake with a limited magnitude in a limited area immediately, or successively larger earthquakes in larger possible areas, if the increase in time-delays continues for further periods of time without a large earthquake.

Any build-up of deformation may be expected to vary very slowly in any particular area depending on convection currents, plate tectonics, distance from subduction zones, and similar phenomena. Since the magnitude of the earthquake would depend on the amount of deformation energy available it is likely that the longer the build-up of deformation the larger the eventual earthquake.

Timescales will depend on current tectonic activity in the particular area. Thus four examples worldwide suggest that time-delays building up for about 1000 days leads to an M =6 earthquake, from 200 to 400 days for an M 4, and between about 4 days and 30 days for magnitude ML = 3.8 and 3.7 earthquakes, respectively.

In the example of build-up of time-delays over 1000 days, say, an example forecast could be as follows (distances and times are approximate and could vary with region and time):

1) A magnitude 6 earthquake may occur at any time within 50 km, say, of the monitoring site.

2) If the time-delays continue to increase for a further 500 days, say, a magnitude 7 earthquake might occur within 100 km, say, of the monitoring site.

3) If the time-delays continue to increase for a further 1000 days, say, a magnitude 8 earthquake might occur within 200 km, say, of the monitoring site.

In Iceland (see below) where routine observations are possible, the input of strain/stress is probably rather greater than elsewhere. Consequently, the duration of the build up of stress is about 40 days for an M=3 earthquake, about 120 days for an M=5, and possibly 200 days for an M=6 earthquake. The effects on shear-wave splitting of the build up of stress are seen at 40 km from an M=5 earthquake.

The high seismicity of the transform zone of the Mid-Atlantic Ridge and the seismic network developed during the SIL Project in Iceland provide good conditions for

stress-forecasting. An example of successful stress-forecasting using data from a station of this seismic network will now be given, noting that this data was collected using natural rather than controlled seismic sources, and surface rather than borehole receivers, and therefore is not an optimal configuration according to the present invention.

Figures1 and 2 show variations in 1997 and 1998 of normalised time-delays in both bands of the shear-wave window at two stations named BJA and KRI respectively. The time-delay data show the expected large scatter, making inferences subject to misleading recognised or unrecognised location-induced trends if the data are sparse, consequently the interpretation below is based principally on Station BJA which has more adequate data.

The middle cartoons in Figure 1 show nine-point moving averages through the time-delays in Band-1 (15°- 45°). BJA has a series of five pronounced minima. A series of least-squares lines through the data are drawn, where each line begins just before the time of a minimum of the moving average (there is some subjectivity here), and ends at the time of a larger earthquake, when there is a comparatively abrupt decrease in time-delays. (The lower cartoons show the magnitudes of all M>=2 earthquakes within 20km of the each station.) The straight-lines show increasing time-delays, implying increasing crack aspect-ratios. The data at BJA show no false alarms, although the variations before the M=4.3 earthquake show unexplained irregularities and are henceforth neglected. The upper cartoons show nine-point moving averages through the time-delays in Band-2 (0° - 15°) with irregular behaviour, and we have been unable to find any correlation with the earthquakes.

Behaviour at BJA: Prior to July, 1998, the middle cartoons for at BJA shows increases in time-delays in Band-1for all four larger earthquakes within 20 km of the station with magnitudes ranging from M=3.5 to M=5.1. The duration and rate of increase varies with the magnitude of the eventual earthquake, and the greatest normalised time-delay, the presumed level of fracture criticality, varies between about 12 ms/km and 14 ms/km.

Behaviour at KRI: Data are sparse and, apart from the changes after July, 1998, there are no discernible variations of splitting in Band-1. The largest earthquake within 20km of KRI is only M=3.7 in February, 1997 and there were no earthquakes within the shear-wave window before this event.

Behaviour at SAU (not shown): Apart from the changes after July, 1998, there are two increases of time delays in Band-1 associated with the same M=4.3 and 5.1 earthquakes which showed changes at BJA at distances of 42km and 43km, respectively, from another station SAU.

Note that both bands of the shear-wave windows at both stations show a decreasing trend over the two-year period (also shown by SAU). This is believed to be caused by the relaxation of stress following the Vatnajökull eruption of 30th September 1996.

It was recognised on 27th October 1998 that the time-delays in Band-1 were increasing from about July, 1998 at both stations BJA and KRI (Figure 1). Five features were thought to be significant: (i) The increase had persisted for nearly four months and (ii) was approximately the same duration and slope as the increases before the M=5 earthquake previously at BJA. (iii) The increase at BJA started at about the lowest level (~4 ms/km) of any of the increases associated with previous earthquakes. (iv) There is less scatter about the line than for previous earthquakes, and (v) the increase at BJA was already nearly 10 ms/km and close to the inferred level of fracture criticality. Many of these features appeared simultaneously at stations BJA and KRI, which are about 38 km apart.

These features suggested that the crust was approaching fracture criticality before an impending larger earthquake. Consequently, stress-forecasts were emailed (27th and 29th October) to the Icelandic Meteorological Office (IMO) in Reykjavik warning of an approaching (but unspecified) earthquake. IMO suggested that the increase in stress might be associated with the M=5.1, 4th June, 1998, earthquake, 10 km from BJA, which was believed to have initiated movement on a previously dormant fault.

In the next ten days, time-delay data were checked and updated and scatter was reduced by plotting only the most reliable data. A meeting of the Scientific Advisors of the National Civil Defence Committee of Iceland (NCDC) was held on 5th November. The stress-forecasts of 27th and 29th October were discussed, together with information about its possible association with the M=5.1, 4th June earthquake. These forecasts were not specific and magnitudes were not suggested. Moreover, the concept of stress-forecasting is new and optimal responses had not been established. Consequently, NCDC were faced with new criteria and the scientific advisors the NCDC decided with justification that no further action need be taken on their behalf. However, IMO and others initiated and intensified investigations of local geophysics and geology in an attempt to identify the potential location.

Further examination of new and updated data showed that from September station SAU also displayed a possible increase of time-delays in Band-1 (later analysis suggested more irregular behaviour at SAU than was initially indicated and the data are not shown). Consequently, an email to IMO was sent on 10th November, 1998, with a specific stress-forecast that an earthquake could occur any time between now (with magnitude M>=5) and end of February (M>=6) if stress kept increasing. These values were estimated from the middle cartoons of Figure 1a, with an earlier smaller magnitude to later larger magnitude window to allow for inaccuracies in the estimated increase and level of fracture criticality.

Three days later, on 13th November, 1998, IMO reported that there had been an M=5 earthquake with epicentre 2 km from BJA at 10.38 that morning (parameters: time 10.38.34, date 13th November, 1998, depth 5.3 km, epicentre 63.949N, 21.344W, and magnitude now estimated as M=4.9). As suggested by IMO, the earthquake appears to be on the same fault as the M=5.1, 4th June, 1998 event. I believe this is a successful stress-forecast within a comparative narrow time magnitude window.

The present invention can be used for stress forecasting volcanic eruptions as well as earthquakes.

CLAIMS

1. A method for stress-forecasting of a seismic event, comprising detecting, at at least one location at a first depth below the Earth's surface, shear-waves emitted from a seismic source at at least one angle between 0° and 90° to the vertical, the source being spaced horizontally from the at least one location and at a second depth greater than or equal to the first depth.

2. A method according to claim 1, wherein said second depth is greater than 500 km.

3. A method according to claim 2, wherein said second depth is greater than 1 km.

4. A method according to claim 3, wherein said second depth is of the order of 2 km.

5. A method according to any preceding claim, wherein shear-waves propagating at an angle less than 50° to the vertical are detected.

6. A method according to claim 5, wherein shear-waves propagating at an angle between 15° and 45° to the vertical are detected

7. A method according to any preceding claim, wherein time-delays between orthogonal polarisations of the shear-waves are analysed.

8. A method according to claim 6, comprising measuring both the duration of the increase in time-delays and the size of the time-delay relative to fracture criticality.

9. Apparatus for stress-forecasting a seismic event, comprising at least one borehole seismic source and at least one borehole seismic receiver, the at least one source being deeper than or at the same depth as the at least one receiver and the at least one source being adapted to generate shear waves upwardly at 0° to 90° to the

vertical in the direction of the at least one receiver.

10. Apparatus according to claim 9, wherein the azimuthal direction of the at least one receiver from the at least one source is at an angle greater than 30° to an average crack strike.

11. Apparatus according to claim 10, wherein said angle is greater than 45°

12. Apparatus according to claim 10, wherein said angle is greater than 60°.

13. Apparatus according to any one of claims 9 to 12, wherein a monitored site comprises one said seismic source and two said seismic receivers.

14. Apparatus according to claim 13, wherein the two receivers are placed in separate boreholes at azimuths spaced in angle from the source borehole.

15 Apparatus according to claim 14, wherein the receivers are placed at azimuths between 0° and 90° apart with respect to the source.

16. Apparatus according to claim 15, wherein the receivers are placed at azimuths approximately 60° apart with respect to the source.

17. Apparatus according to any one of claims 13 to 16, comprising a plurality of monitored sites.

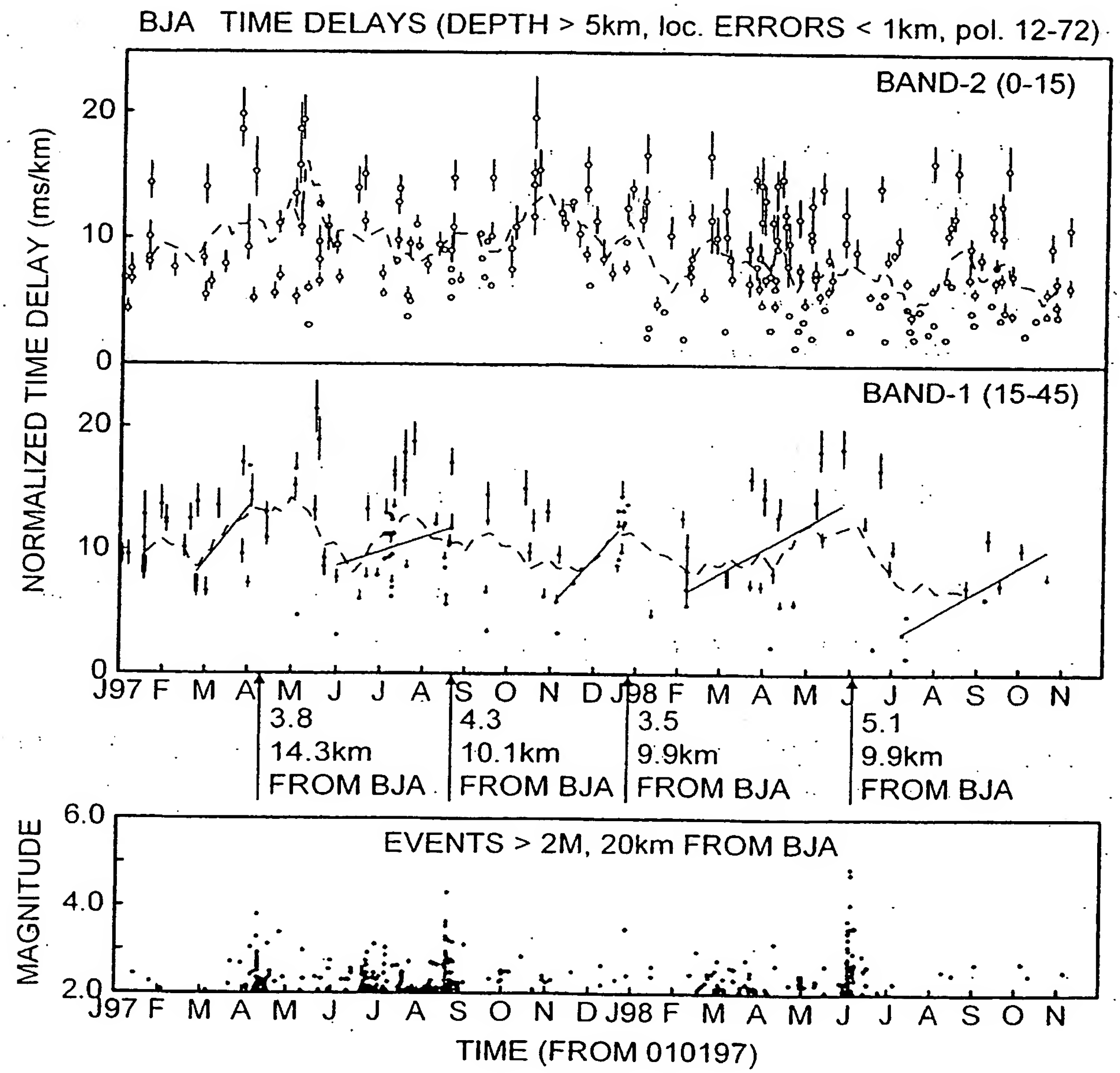
BJA TIME DELAYS (DEPTH > 5km, loc. ERRORS < 1km, pol. 12-72)
BAND-2 (0-15)
BAND-1 (15-45)
NORMALIZED TIME DELAY (ms/km)
20
10
0
J97 F M A M J J A S O N D J98 F M A M J J A S O N
3.8
14.3km
FROM BJA
4.3
10.1km
FROM BJA
3.5
9.9km
FROM BJA
5.1
9.9km
FROM BJA
EVENTS > 2M, 20km FROM BJA
MAGNITUDE
6.0
4.0
2.0
TIME (FROM 010197)

FIG. 1

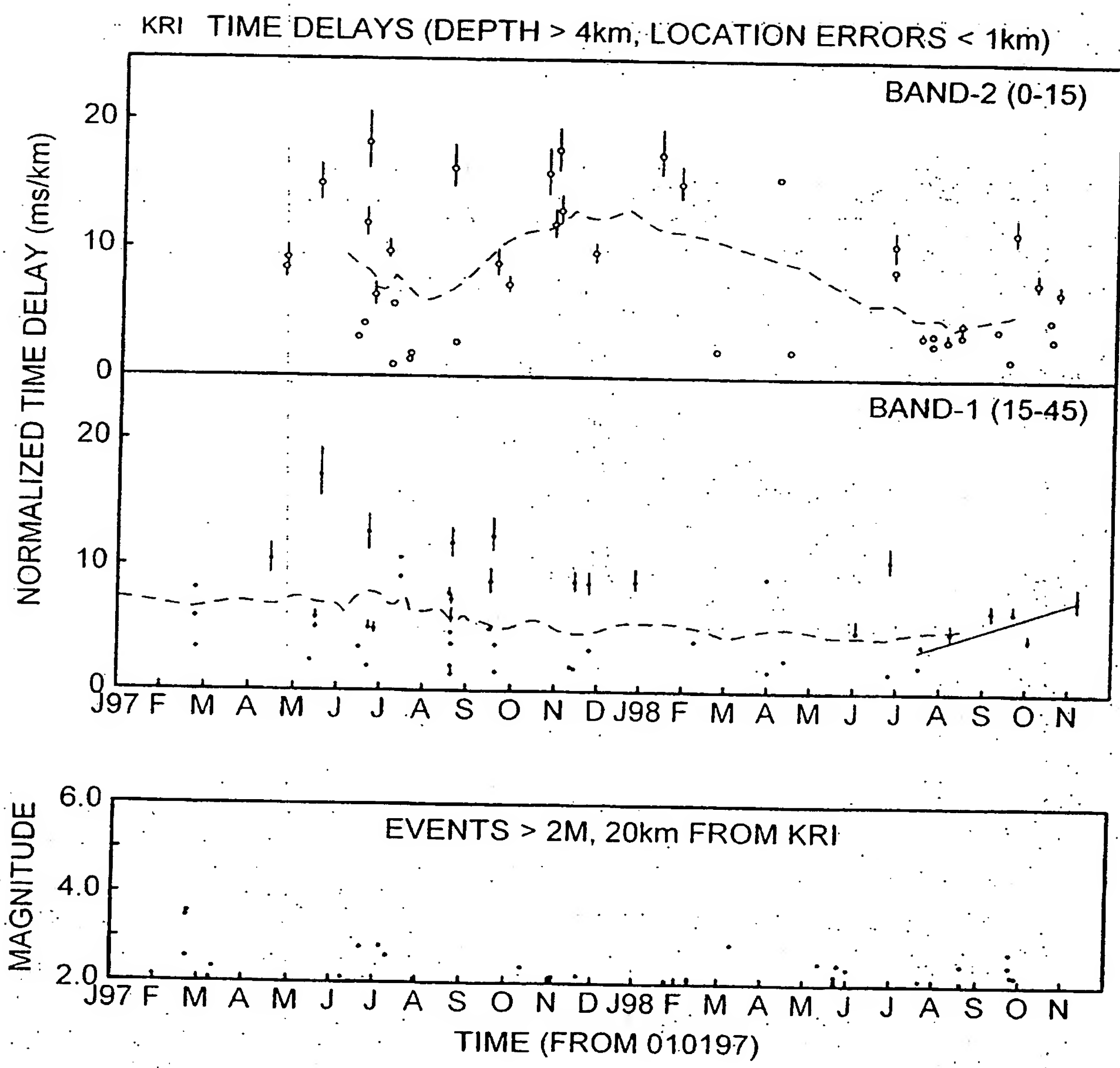
KRI TIME DELAYS (DEPTH > 4km, LOCATION ERRORS < 1km)
BAND-2 (0-15)
BAND-1 (15-45)
NORMALIZED TIME DELAY (ms/km)
20
10
0
J97 F M A M J J A S O N D J98 F M A M J J A S O N
6.0
4.0
2.0
MAGNITUDE
EVENTS > 2M, 20km FROM KRI
TIME (FROM 010197)

FIG. 2

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 00/01137

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01V1/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01V

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
INSPEC, EPO-Internal, COMPENDEX, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 771 170 A (COLE MARY J ET AL) 23 June 1998 (1998-06-23) column 7, line 13 - line 15 column 7, line 32 - line 46; figures 1,2	1,7,9, 13-17
A	TROKHAN A M: "FUNDAMENTAL METROLOGICAL PROBLEMS. PHYSICAL MEASUREMENTS IN EARTHQUAKE PREDICTION" MEASUREMENT TECHNIQUES,US,CONSULTANTS BUREAU. NEW YORK, vol. 40, no. 6, 1 June 1997 (1997-06-01), pages 505-510, XP000778900 ISSN: 0543-1972 page 506, line 5 - line 12; figure 1	1,7,8

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
20 July 2000	28/07/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Swartjes, H

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 00/01137

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	CRAMPIN S: "SHEAR-WAVE SPLITTING IN A CRITICAL CRUST: THE NEXT STEP" REVUE DE L'INSTITUT FRANCAIS DU PETROLE,FR,EDITIONS TECHNIP. PARIS, vol. 53, no. NO. SPEC.), September 1998 (1998-09), pages 749-763, XP000831999 ISSN: 1294-4475 page 751, paragraph 1.1	1,7-10, 14
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/GB 00/01137

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		WO 9809182 A	05-03-1998
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